Safety Evaluation of the FuelMaker Home Refueling Concept

Photo courtesy of FuelMaker Corporation

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1. Approach
2. Supporting Analyses
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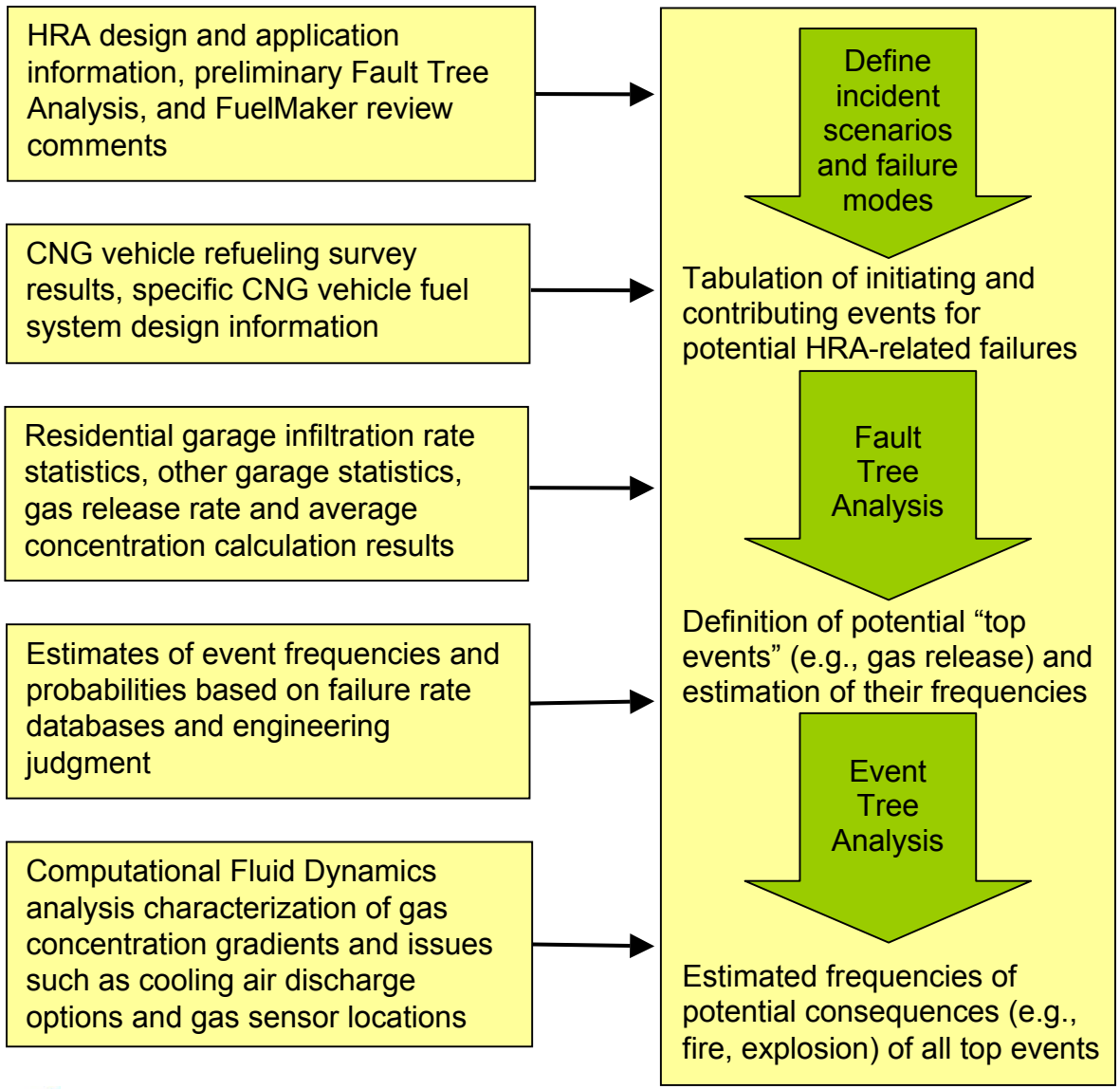
1. **Approach**
2. **Supporting Analyses**
3. **Safety Evaluation Results**
4. **Current Status**

The overall objective of this project was to carry out a safety evaluation of the FuelMaker Home Refueling Appliance (HRA) considering it's application to refueling CNG vehicles inside residential garages

- Independent
- Using established failure and consequence probability estimating methodologies

Photo courtesy of FuelMaker Corporation


HRA design and application information, preliminary Fault Tree Analysis, and FuelMaker review comments
CNG vehicle refueling survey results, specific CNG vehicle fuel system design information
Residential garage infiltration rate statistics, other garage statistics, gas release rate and average concentration calculation results
Estimates of event frequencies and probabilities based on failure rate databases and engineering judgment
Computational Fluid Dynamics analysis characterization of gas concentration gradients and issues such as cooling air discharge options and gas sensor locations
Define incident scenarios and failure modes
Tabulation of initiating and contributing events for potential HRA-related failures
Fault Tree Analysis
Definition of potential "top events" (e.g., gas release) and estimation of their frequencies
Event Tree Analysis
Estimated frequencies of potential consequences (e.g., fire, explosion) of all top events

Define incident/event scenarios

- Initiating event
- Contributing events
- Top event
  - An event, e.g., leak
  - Not a consequence, e.g., fire
- Event sequence

51 incident/event scenarios

- Equipment failure (17 scenarios), e.g., hose leak or rupture
- Human error (13 scenarios), e.g., drive away event
- Misuse (13 scenarios), e.g., filling a propane bottle
- Maliciousness (4 scenarios), e.g., neighbor shuts off gas or electric supply to HRA
- External events (4 scenarios), e.g., vehicle strike, gas supply pipe break

- Incident scenarios grouped by top event
- Fault trees constructed leading to each top event (11 defined)
- Frequencies of initiating events, probabilities of contributing events estimated
  - Database of component failure rates
  - Human error statistics
  - CNG vehicle design, experience survey
  - Engineering judgement
- FTA Boolean algebra gives top event frequency
  - Misuse: failures/units installed/year
  - Others: failures/units/year

Fault tree top events

1: HRA continuous full flow (0.67 scfm) discharge into garage

2: CNG vehicle fuel tank blowdown into garage

3: CNG vehicle fuel tank blowdown through HRA to outside garage

4: HRA continuous low flow (0.22 scfm) leak into garage

5: HRA low flow gas release outside garage

6: Gas release into garage by filling propane bottle or inflatable

7: Gas release into garage by attempting to fit torch to HRA

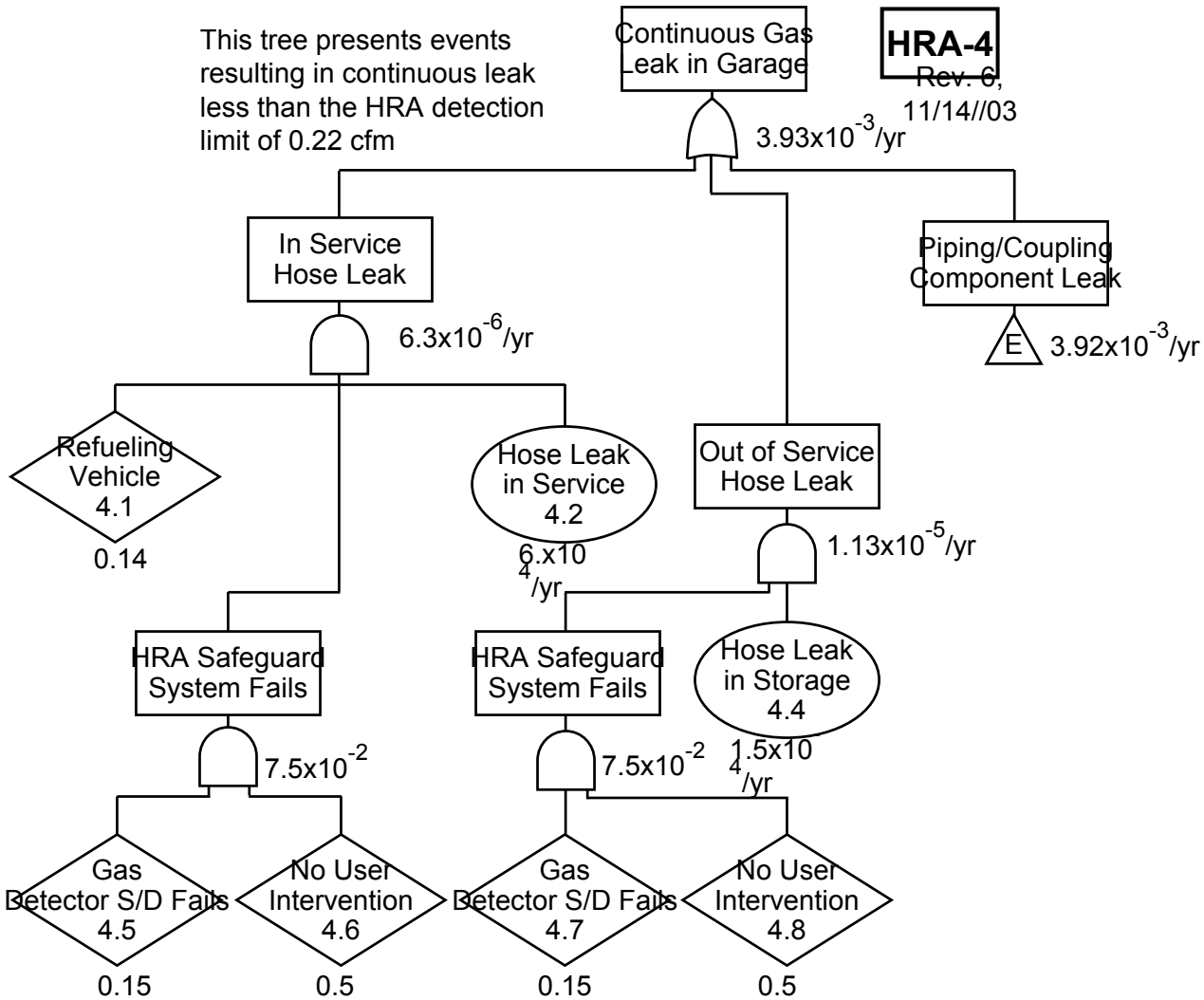
8: Gas release into garage due to gas piping failure after vehicle striking HRA

9: Air ingress into HRA, flammable mixture formation, deflagration

10: Gas release into garage due to buffer tank installation

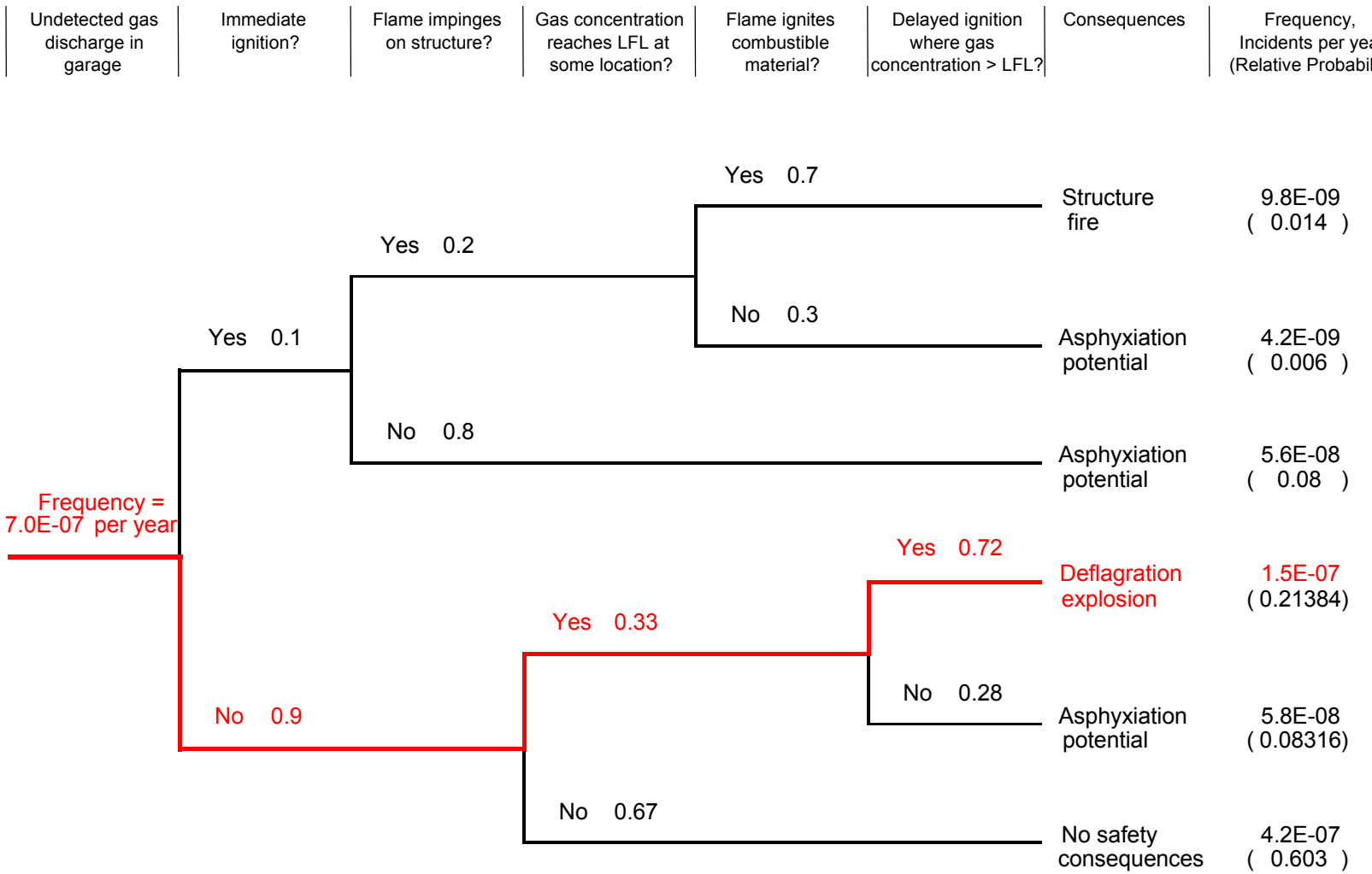
11: Gas release into garage due to long hose extension installation

Example Fault Tree



- FTA predicts failure frequency, not frequency of consequence (e.g., fire or deflagration frequency
- ETA used to extend fault tree top events to consequences having safety implications
- Event trees branch to alternative consequences
- Probabilities of 2 legs of each branch sum to 1
- Supporting analyses used to estimate event tree probabilities
  - Garage infiltration characterization
  - Average garage gas concentration calculations
  - Computation fluid dynamics calculations to estimate magnitude of gradients

General Event Tree Form (most top events)



1 Approach

2 **Supporting Analyses**

3 Safety Evaluation Results

4 Current Status

- Garage infiltration rate of critical importance
  - Determines likelihood of gas release causing >LFL concentrations
- Infiltration characterized by ACH

$$ACH = Q/V$$

Q = infiltration rate (scfm)

V = Garage volume (ft^3)

- Calculate Q from ASHRAE/LBL model and guidelines
- Need:
  - Garage characteristics data (survey of 33 residential garages in the U.S. and Canada)
  - Comparison of measurements with model

Garage Infiltration (ACH) Measurements

- Tracer gas decay method (ASTM 1990)
  - Inert, nontoxic, nonreactive, easily detected gas (sulfur hexafluoride) released in closed garage
  - Gas concentration, wind speed, and temperatures recorded
  - ACH calculated from gas concentration decay rate
  - Equations are documented in ASHRAE and ASTM
  - Measurements carried out using NREL equipment

Spring, Texas, House Garage ACH Measurement

Fremont, California, Condominium Garage ACH Measurement

2-car garage in condominium development in Fremont (between Oakland and San Jose)

Canyon-like environment provides substantial wind shielding to garages

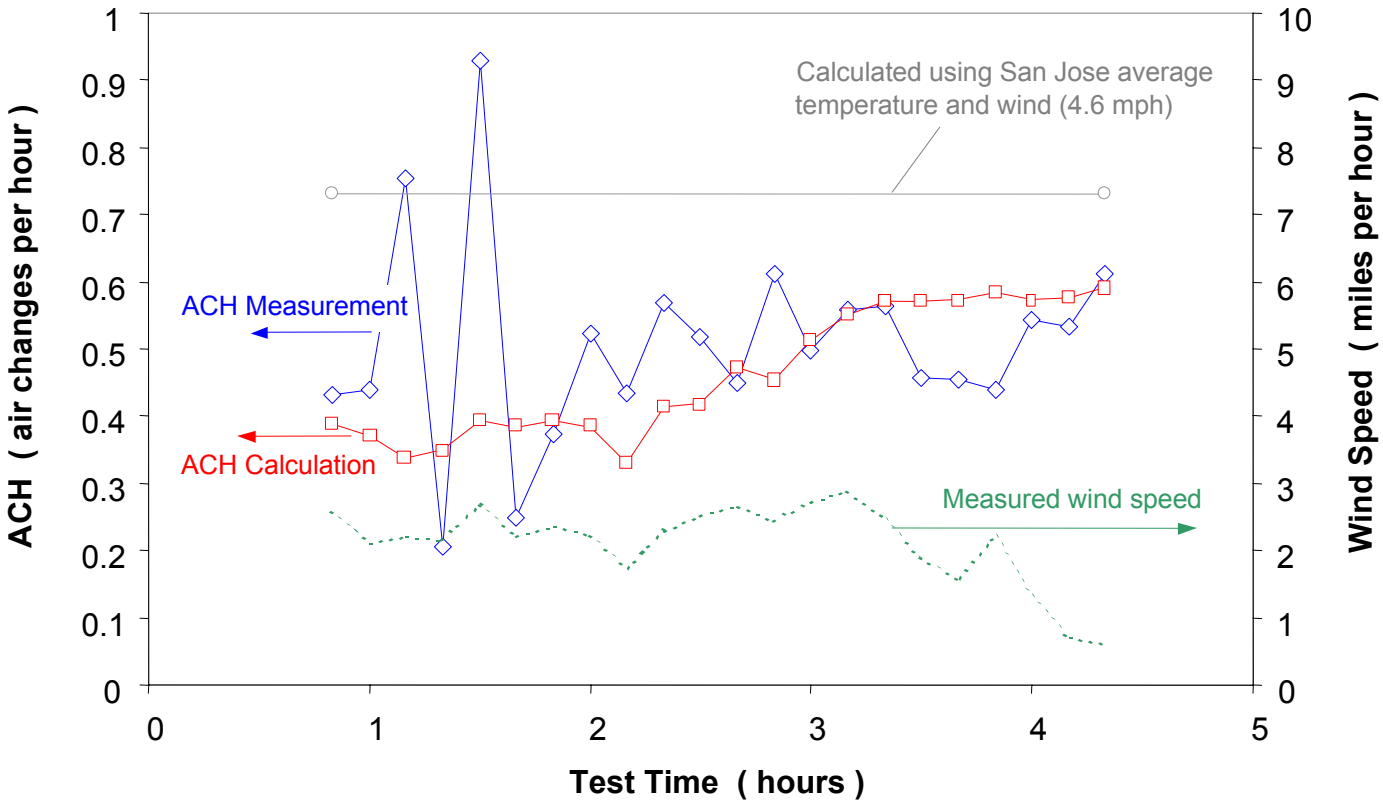
San Jose, California, House Garage ACH Measurement

Typical 2-car garage attached to house

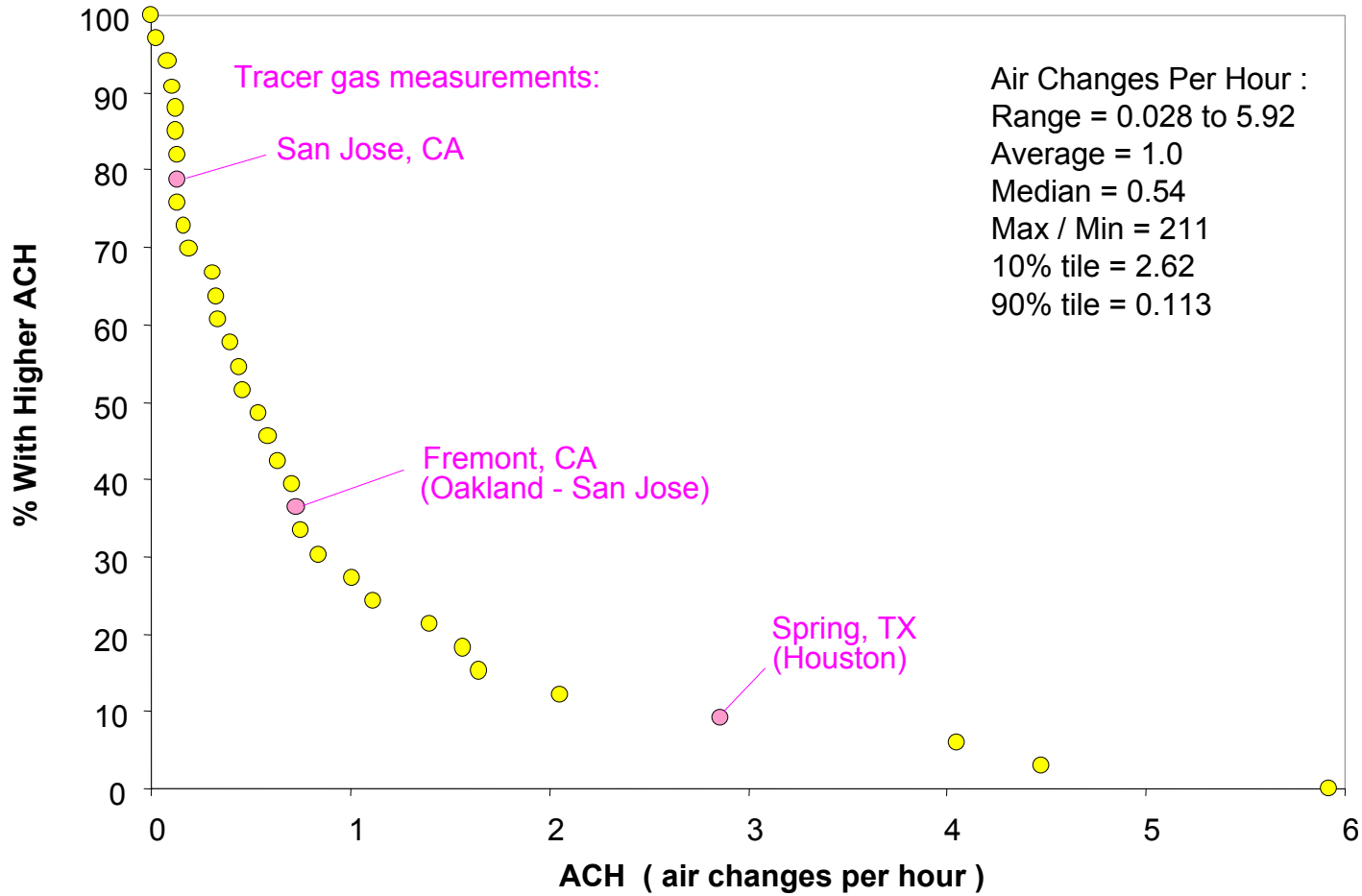
Paneled door has vinyl flap seals

Fremont, California, Condominium Garage ACH Measurement

- Garage door vent was sealed up to simulate “tighter” garage
- Wind speed averaged about one half of area average
- Calculation-measurement agreement is quite good:



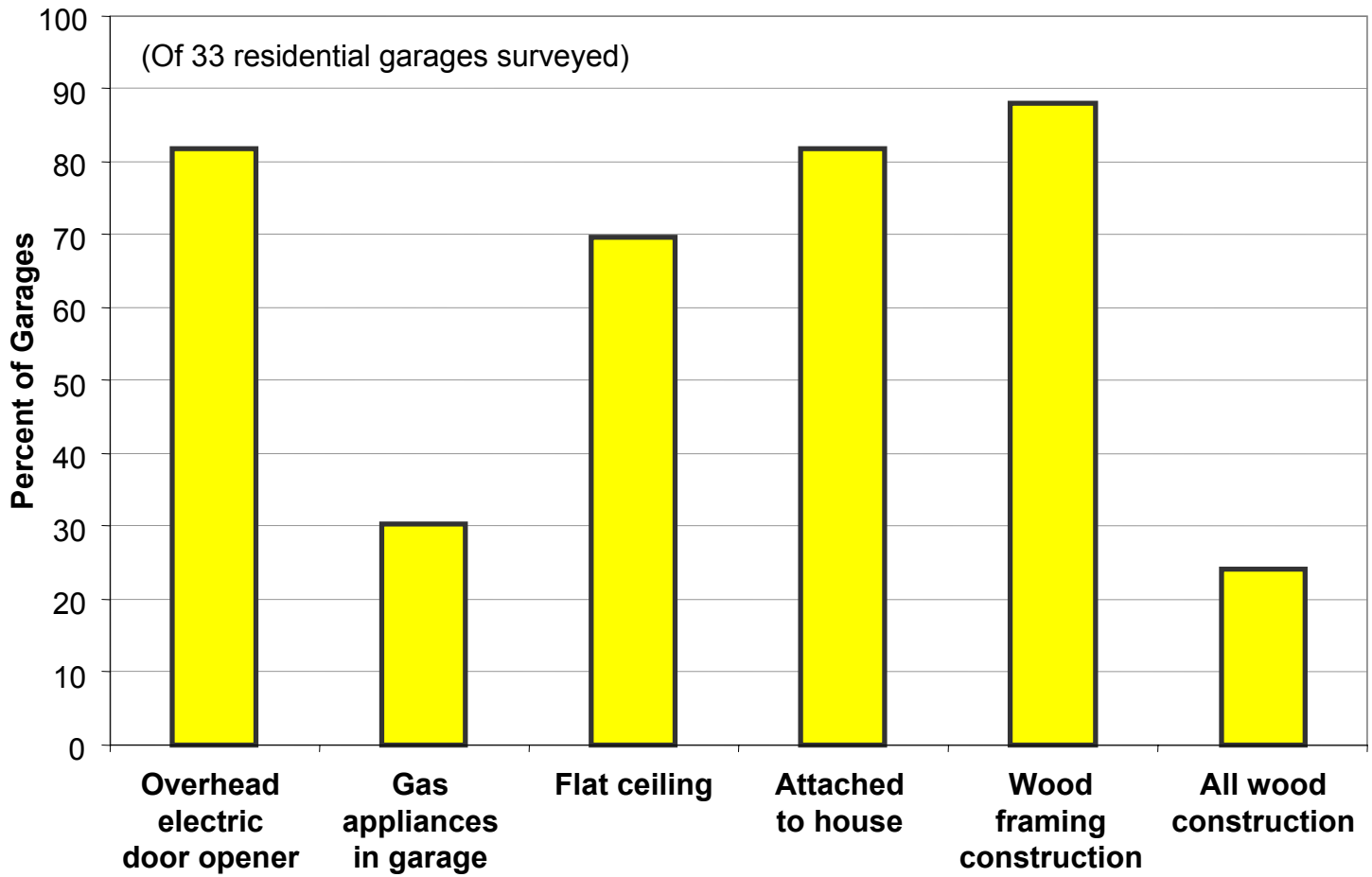
Calculated Garage Infiltration Rates (ACH) based on average local winds and temperatures



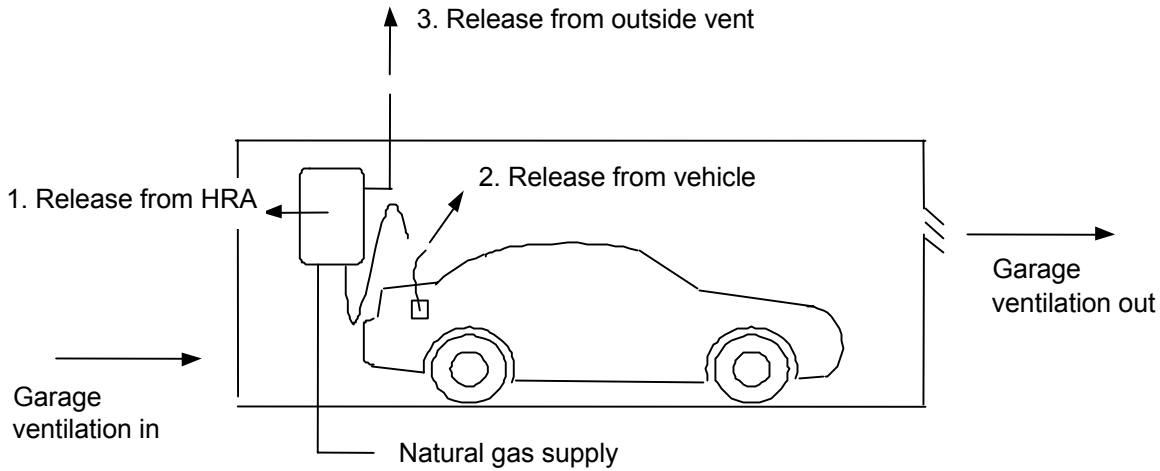
- Garage ACH statistical distribution
  - Provides input needed for event tree probabilities
  - Three categories of garages

Garage Characteristics	ACH Range	% of Garages
Doors weather-stripped, no vents	< 0.25 /hr	~ 33%
Tight doors, no vents	0.25 /hr – 1 /hr	~ 33%
Gaps around doors, or vents	> 1 /hr	~ 33%

Garage survey statistics (supported event tree probabilities)

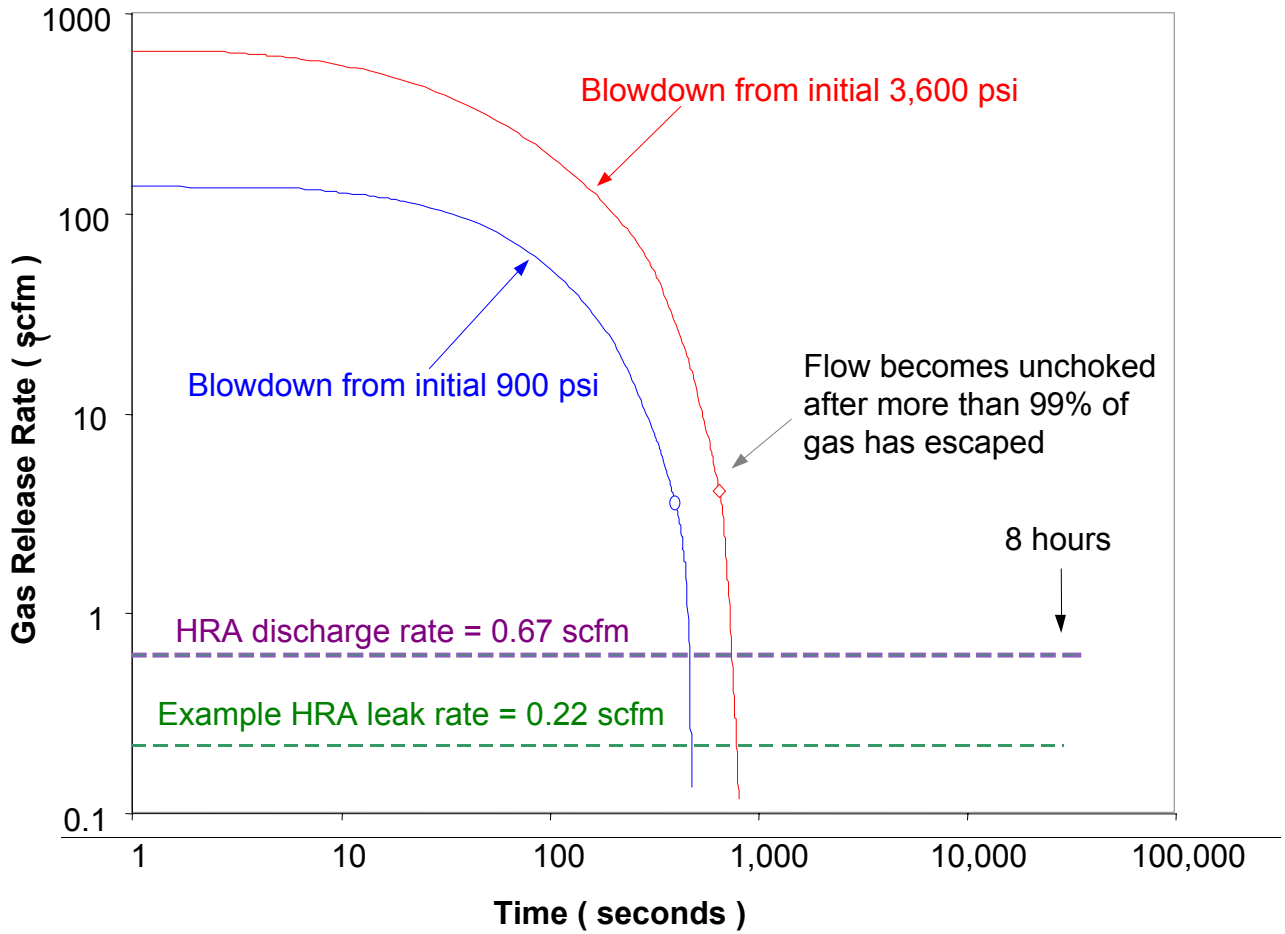


Three types of gas releases possible for HRA use in residential garage:



- Calculated worst-case blowdown from vehicle fuel tank (Honda Civic GX example)
- Compared with HRA discharge and leak rates
- Calculated average garage gas concentrations for these blowdown, discharge, and leak rates

Blowdown compared to HRA discharge and leak



Gas Concentration Calculations

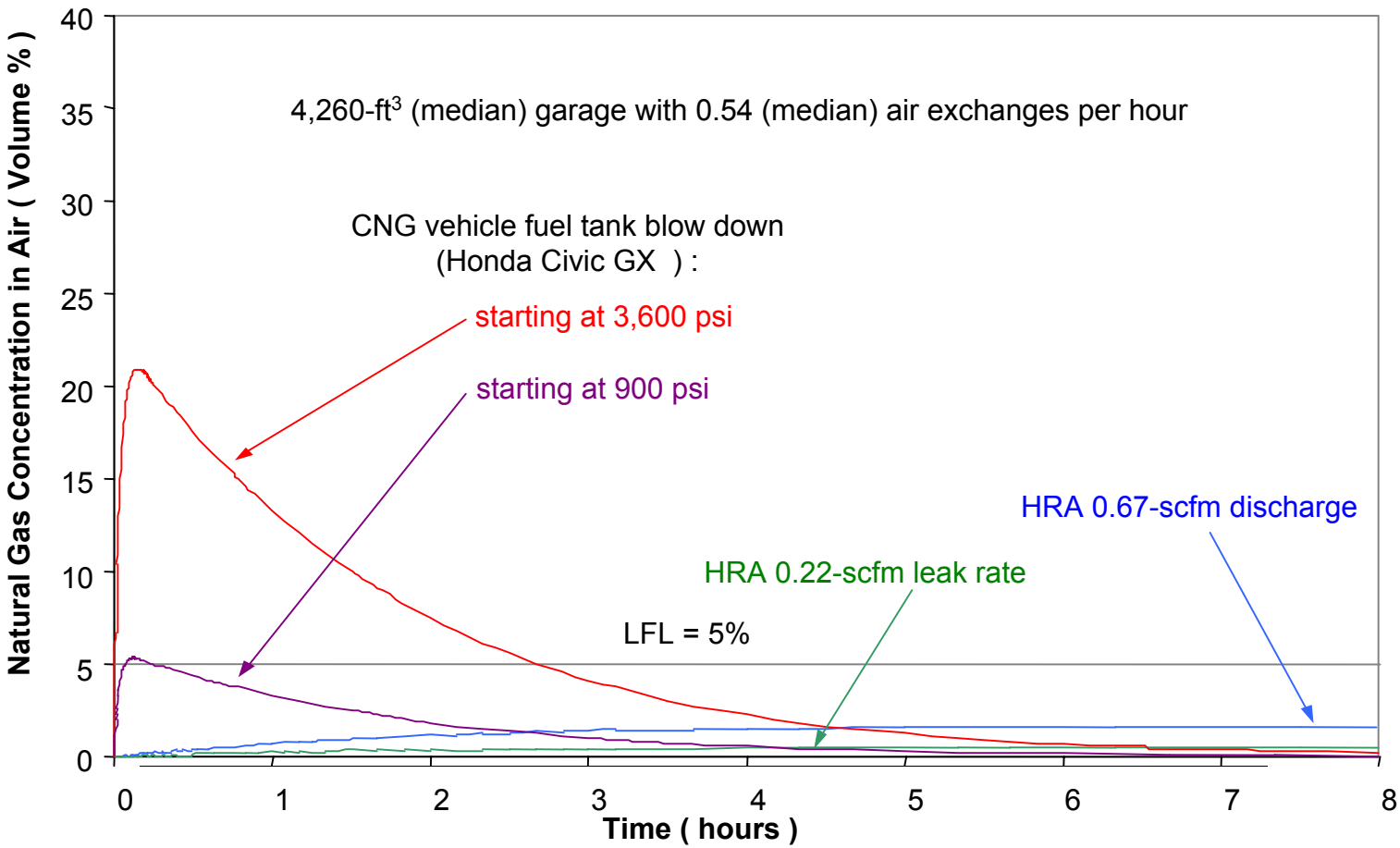
Average (i.e., fully mixed) gas concentration in garage calculated and compared to LFL for:

- Vehicle blowdown, HRA discharge, HRA leak
- Various garage sizes and infiltration (ACH) rates

Calculations performed for:

- Median garage volume and median ACH
- Median garage volume and tenth percentile ACH
- Median garage volume and ninetieth percentile ACH
- Tenth percentile garage volume and median ACH
- Ninetieth percentile garage volume and median ACH

Example result: Median garage with median ACH



Gas Concentrations Calculation Conclusions

- HRA discharge (0.67 scfm) reaches LFL ~8 hr for:
  - Median volume
  - 10th percentile ACH (0.113/hr)
- HRA leak (0.22 scfm) does not reach LFL for any calculated condition
  - Reaching LFL requires ACH of 0.07/hr for median volume garage at >30 hr
- Full tank blowdown immediately exceeds LFL for all calculated conditions

Computation fluid dynamics analyses were performed to:

- Predict time dependent evolution of gas concentrations
  - HRA discharge
  - HRA leak
- Estimate the magnitude of gas concentration gradients
- Suggest best location for gas sensor
- Evaluate HRA cooling air discharge configuration

Calculation cases (all near median garage)

Undetected gas leak (0.22 scfm)

- Case 1
  - Median garage ACH
  - HRA fan discharge into garage
- Case 2
  - Median garage ACH
  - HRA fan discharge outside garage

Nominal failure

Undetected full flow gas discharge (0.67 scfm)

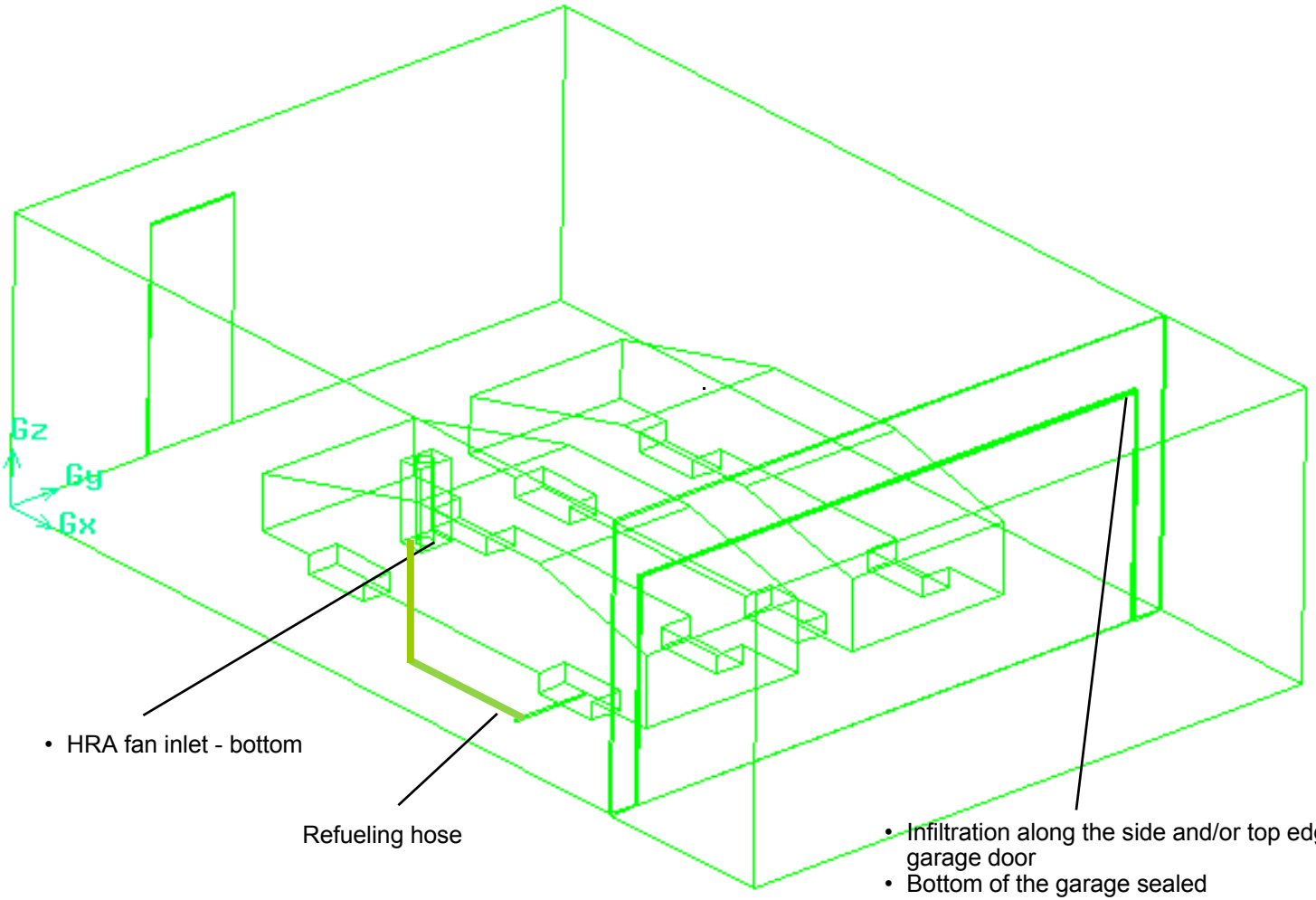
- Case 3
  - Low garage ACH (30th percentile)
  - HRA fan discharge into garage
- Case 4
  - Low garage ACH
  - HRA fan discharge outside garage

Worst case failure

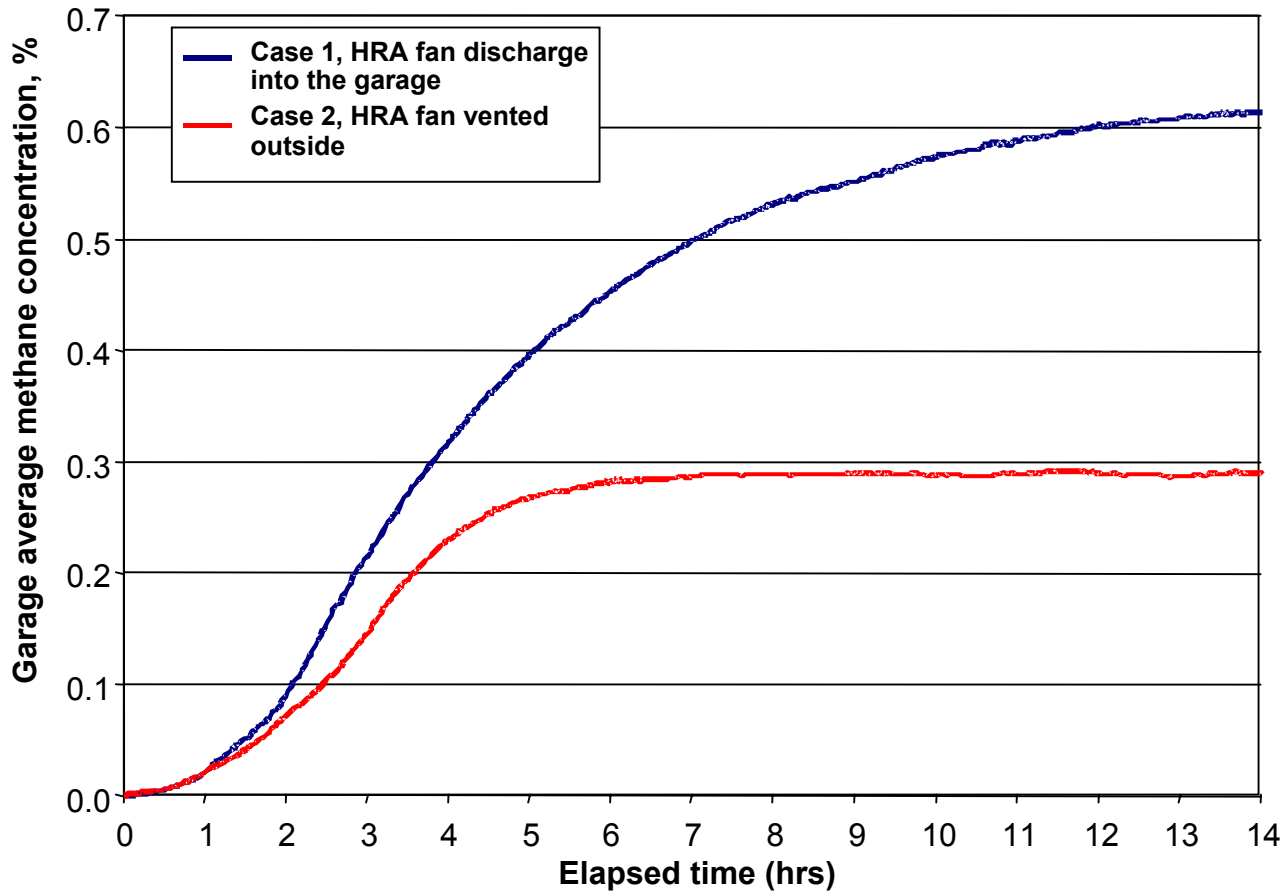
- Case 5
  - Low garage ACH
  - HRA fan off/discharge blocked

Worst case failure

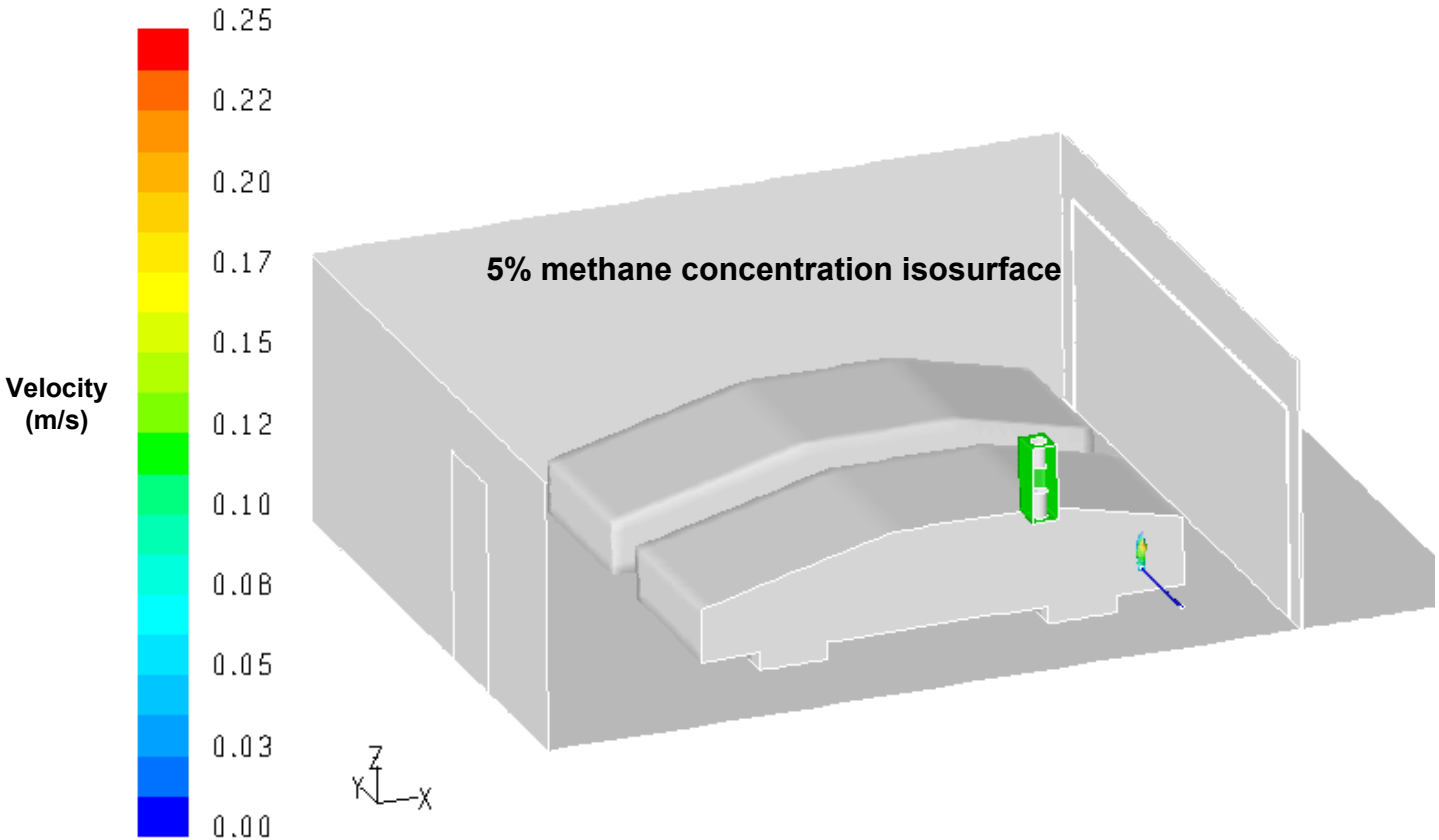
Garage geometry: 4,500 ft^3



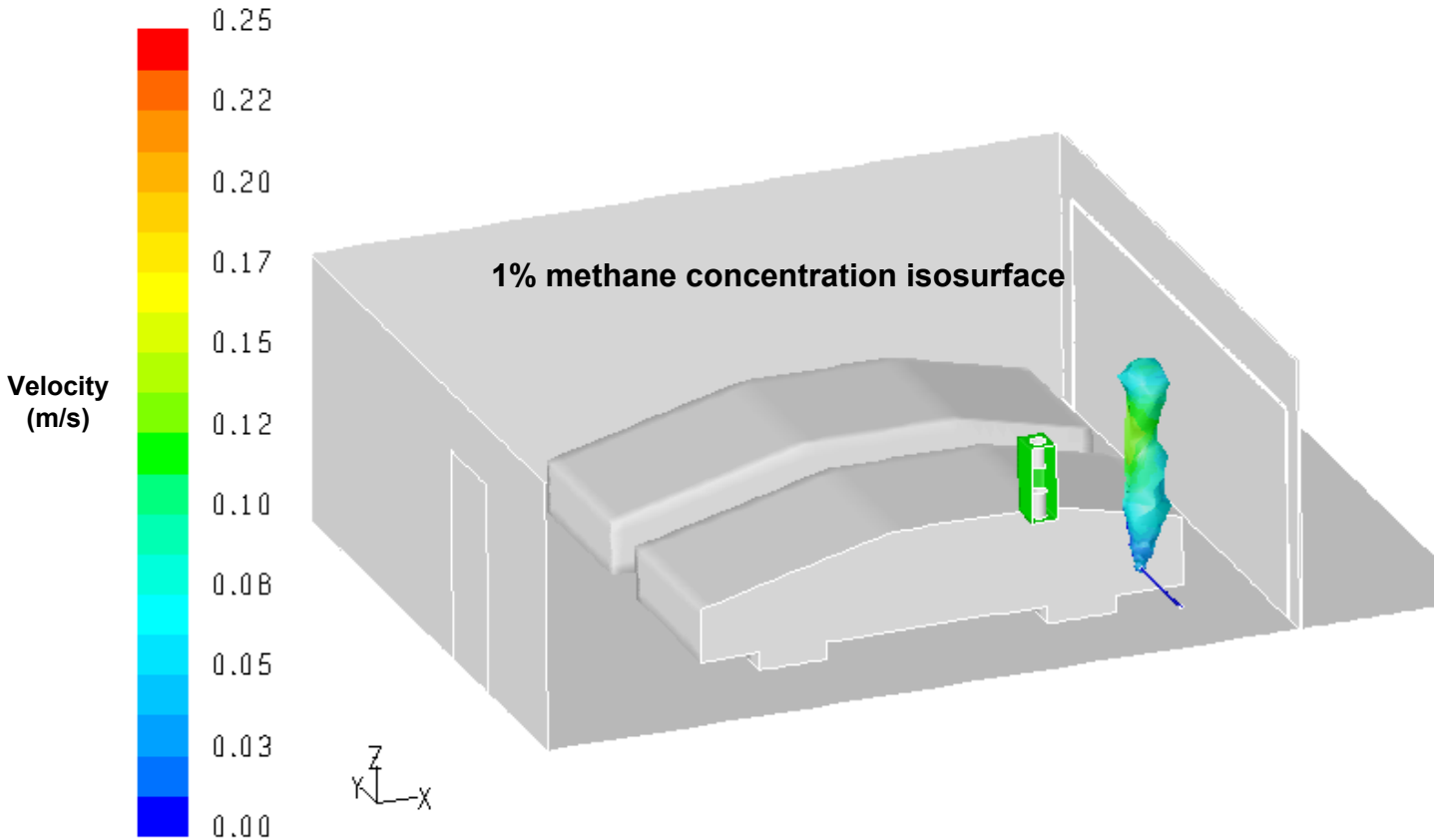
Garage volume average concentrations, gas leak, median ACH



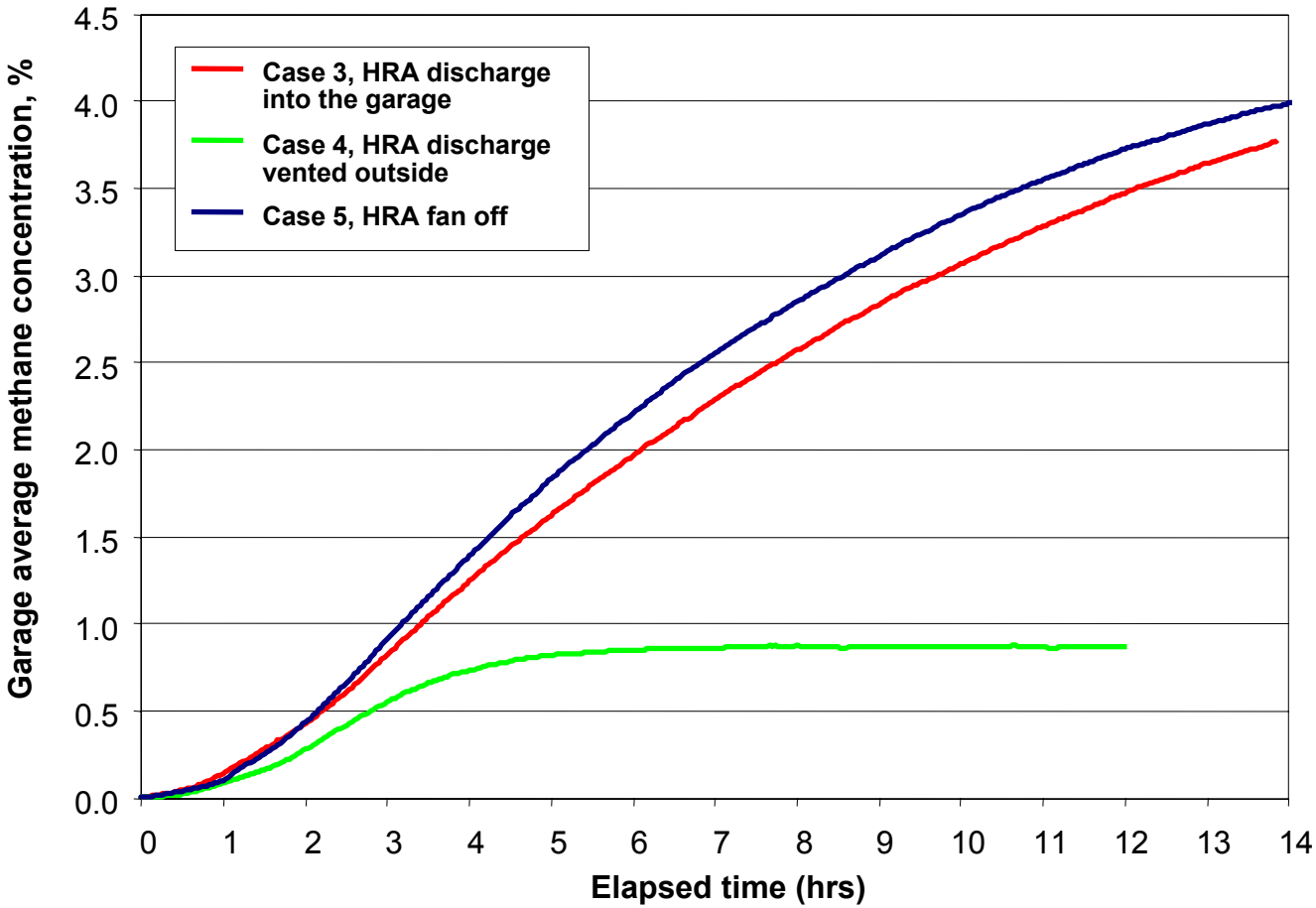
Surface of 5% methane concentration at steady state (~14 hr), Case 1, gas leak, median ACH, HRA fan discharge inside



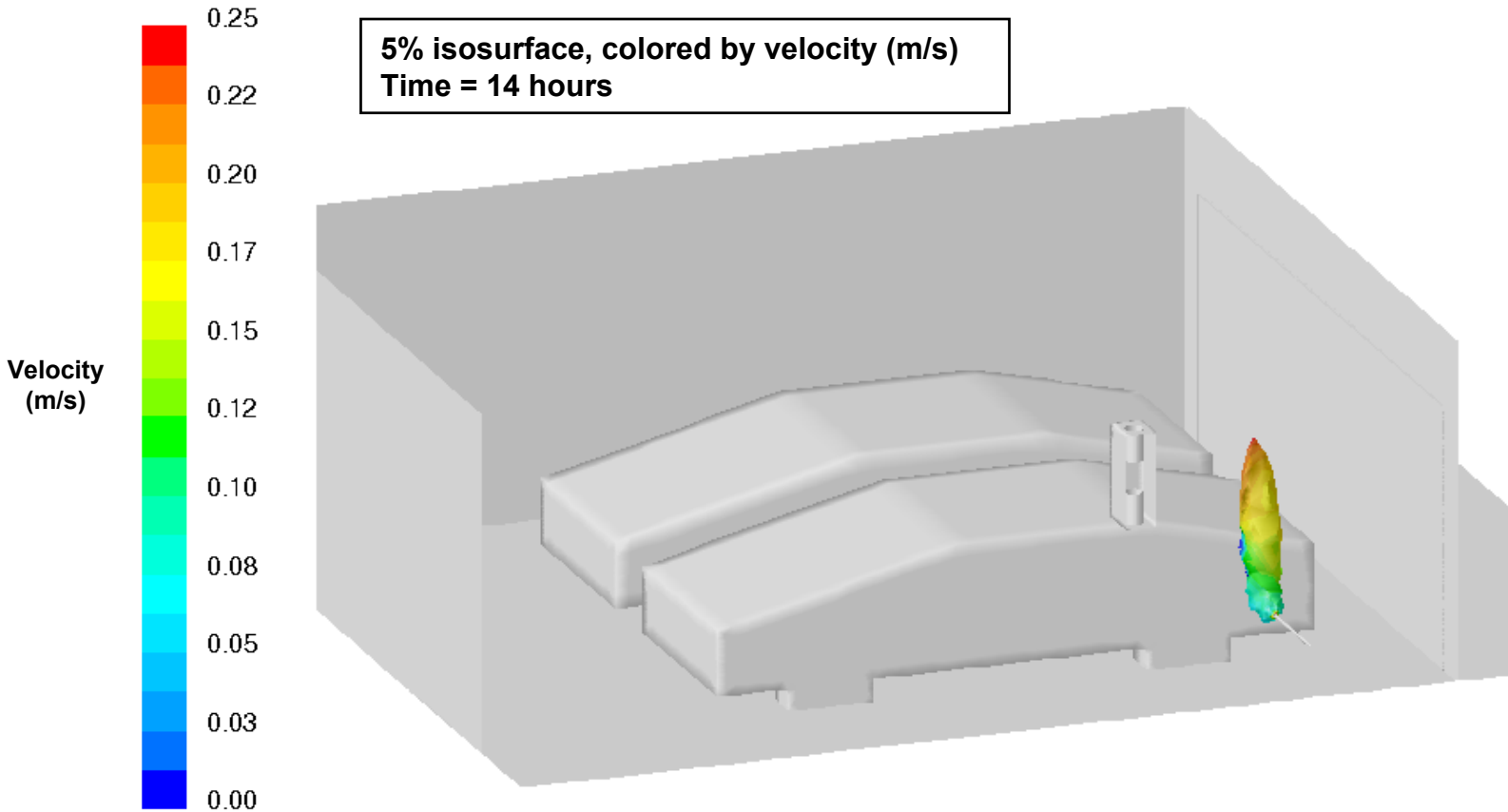
Surface of 1% methane concentration at steady state (~14 hr), Case 1, gas leak, median ACH, HRA fan discharge inside



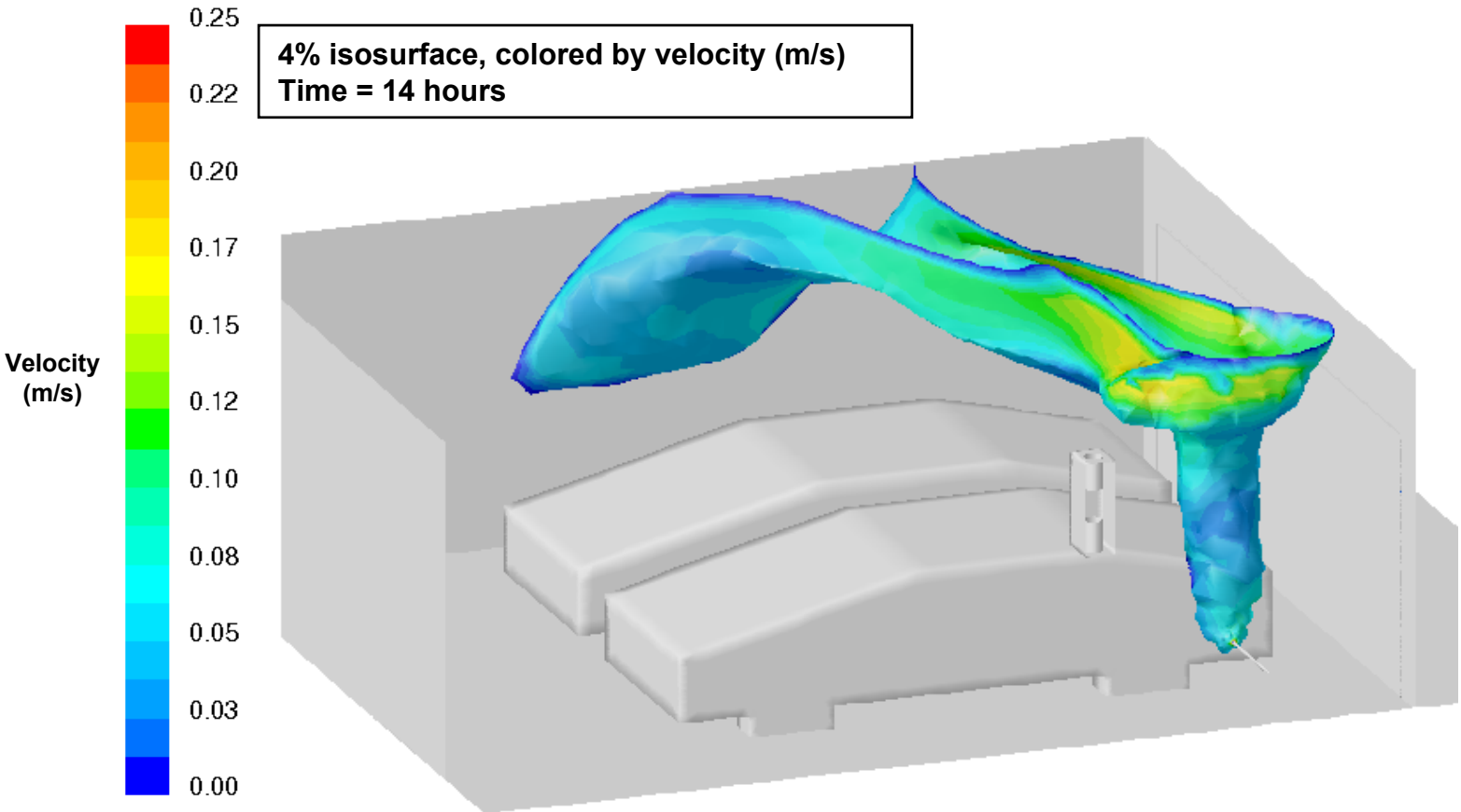
Garage volume average concentrations, gas discharge, low ACH



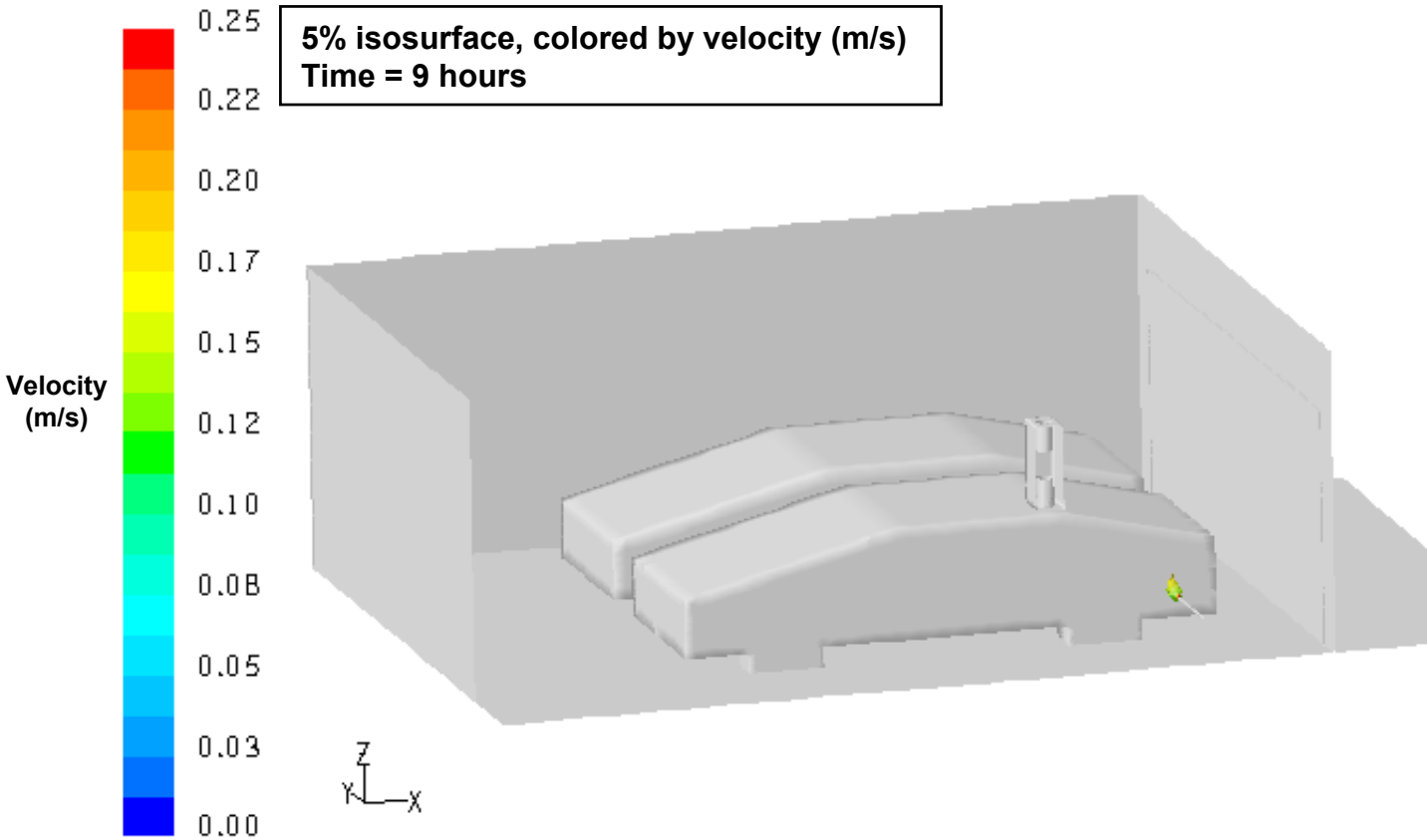
Surface of 5% methane concentration at 14 hr, Case 3, gas discharge, low ACH, HRA fan discharge inside



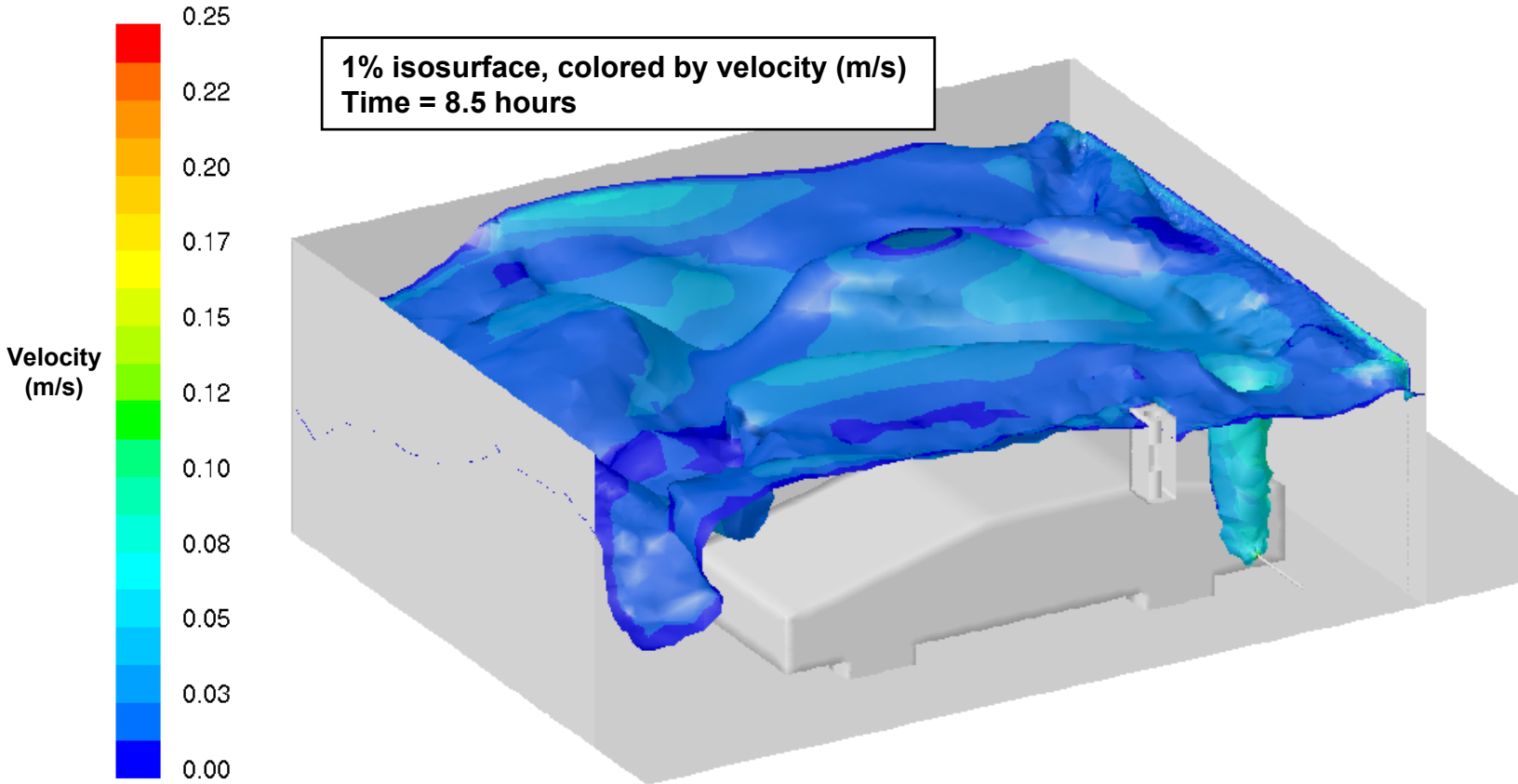
Surface of 4% methane concentration at 14 hr, Case 3, gas discharge, low ACH, HRA fan discharge inside



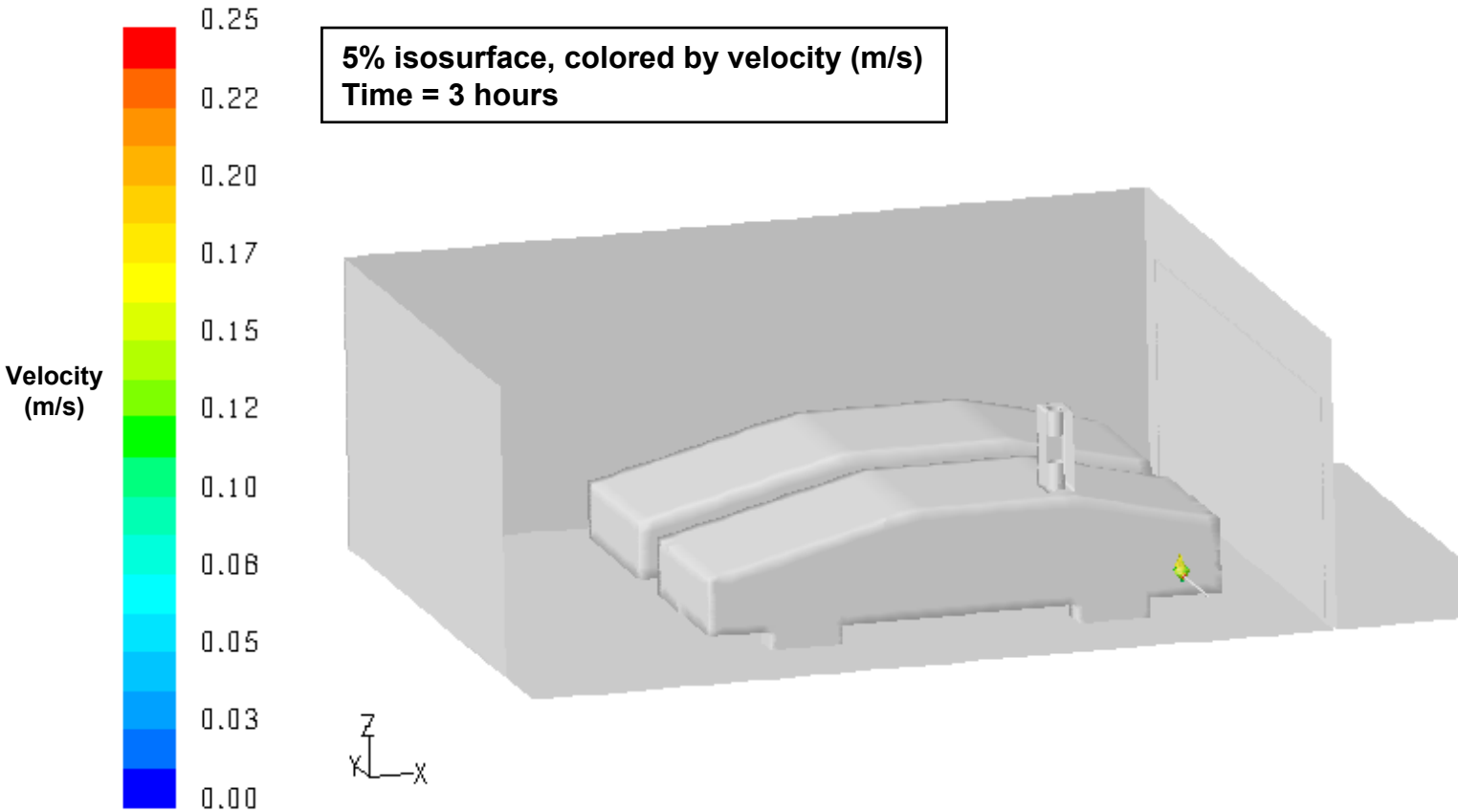
Surface of 5% methane concentration at 9 hr (steady state), Case 4, gas discharge, low ACH, HRA fan discharge outside



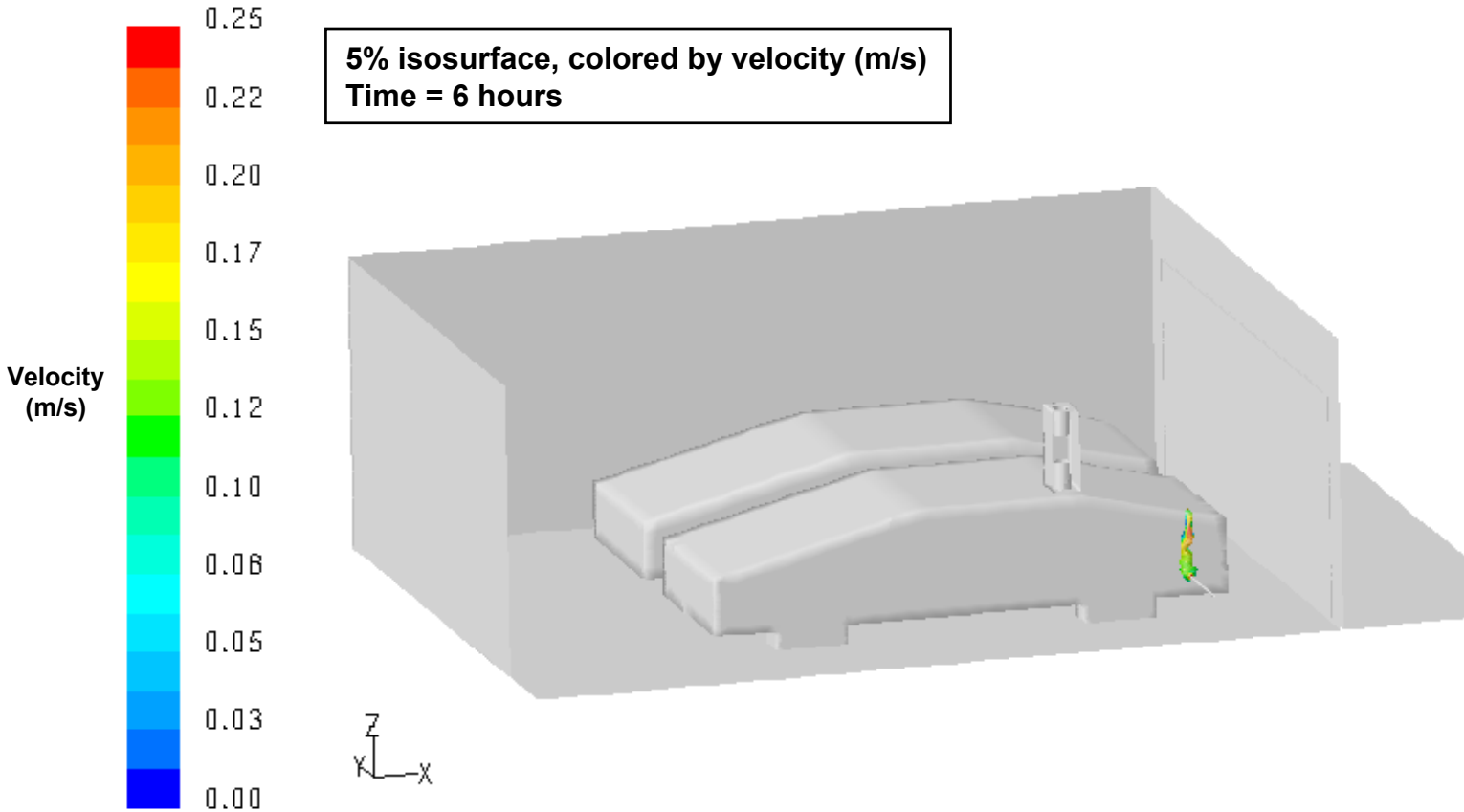
Surface of 1% methane concentration at 8.5 hr (steady state), Case 4, gas discharge, low ACH, HRA fan discharge outside



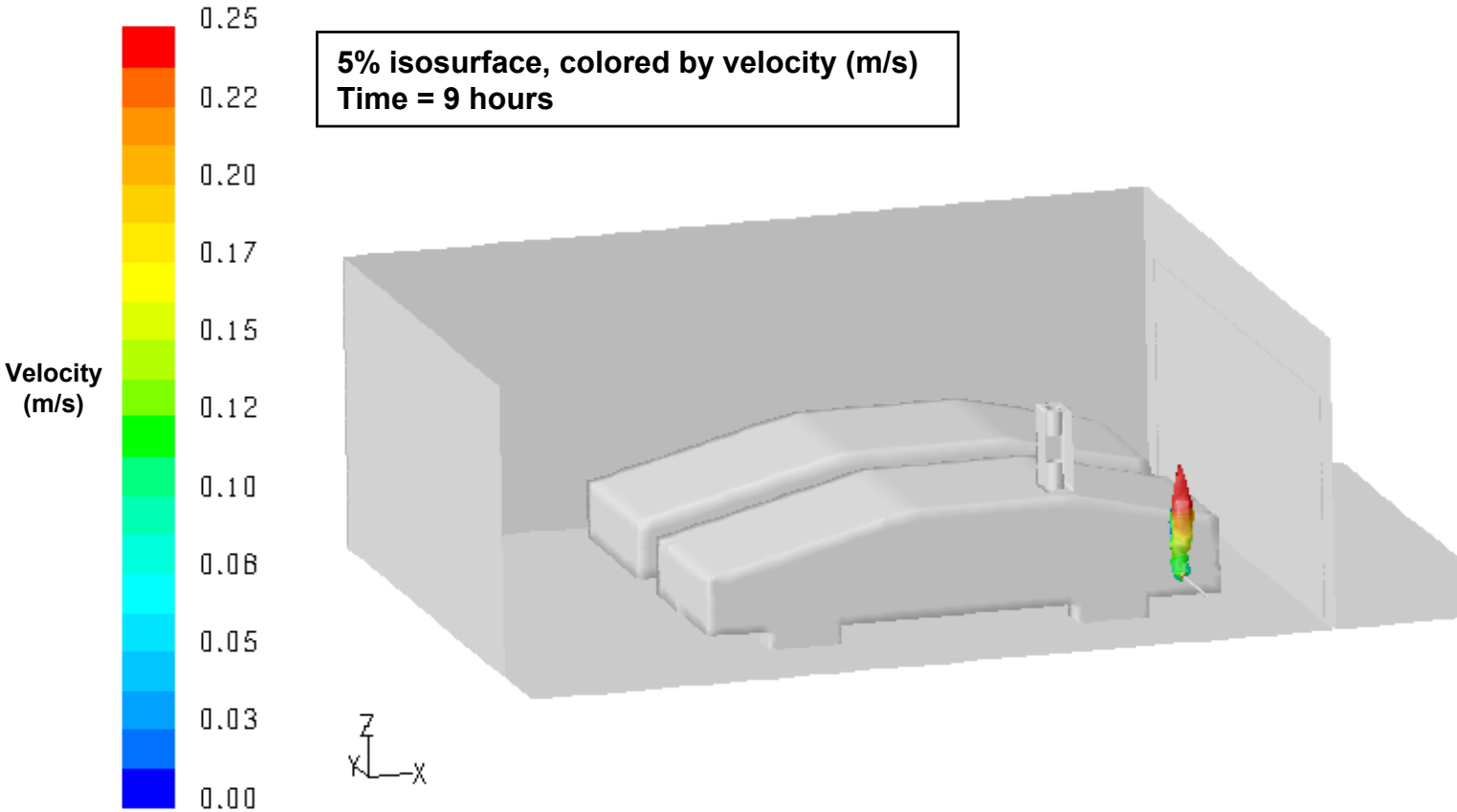
Surface of 5% methane concentration at 3 hr, Case 5, gas discharge, low ACH, HRA fan off



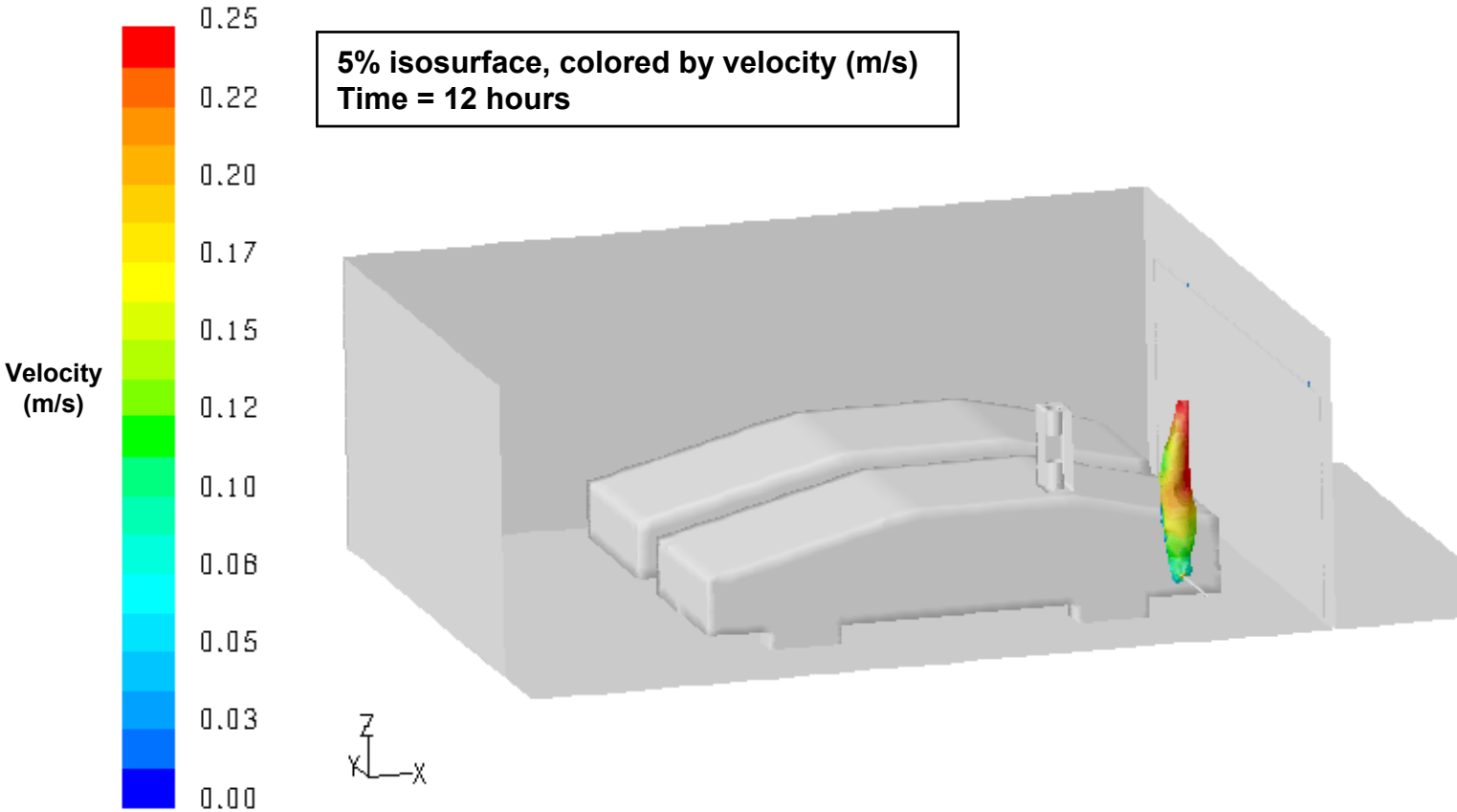
Surface of 5% methane concentration at 6 hr, Case 5, gas discharge, low ACH, HRA fan off



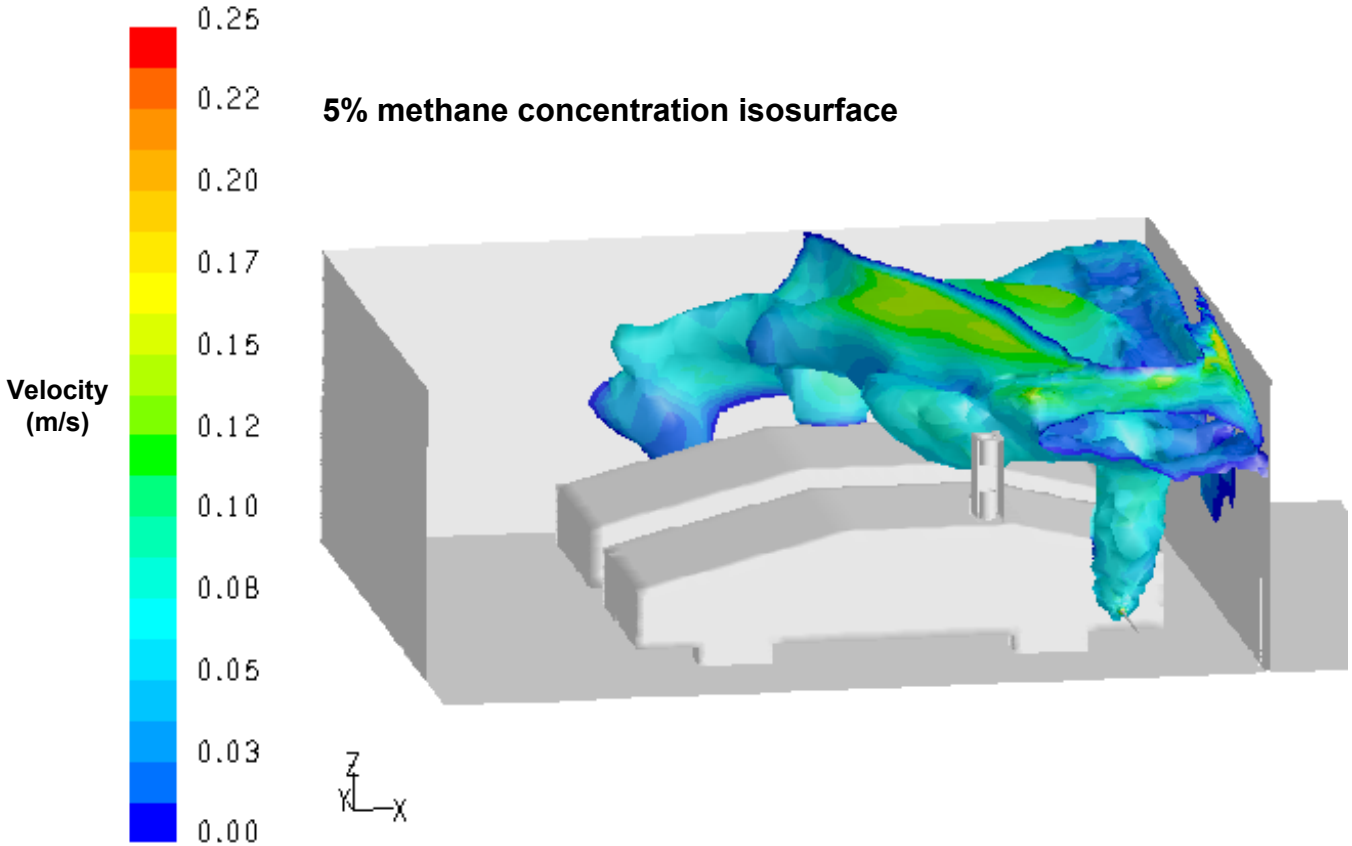
Surface of 5% methane concentration at 9 hr, Case 5, gas discharge, low ACH, HRA fan off



Surface of 5% methane concentration at 12 hr, Case 5, gas discharge, low ACH, HRA fan off



Surface of 5% methane concentration at steady state (>14 hr), Case 5, gas discharge, low ACH, HRA fan off



Computation Fluid Dynamics Conclusions

- Gas leak, median ACH
  - Flammable methane concentrations near ignition source unlikely
  - Region of even 1% methane concentration only directly above leak
  - Same conclusions regardless of where HRA fan discharges
- Gas discharge, low ACH, HRA fan discharge inside
  - Flammable methane concentrations confined to above discharge, do not reach garage ceiling
  - 4% methane concentrations extend along ceiling over much of garage volume
- Gas discharge, low ACH, HRA fan discharge outside
  - Region of flammable methane concentrations reduced substantially
  - Confined to very near discharge

Computation Fluid Dynamics Conclusions (continued)

- Gas discharge, low ACH, HRA fan off (vent blocked)
  - Flammable methane concentrations extend along ceiling over much of garage volume at steady state
  - Much more than 14 hr required to reach steady state
- Locating gas sensor at ceiling above vehicle fuel tank receptacle best, but inside HRA in cooling air path appears ok

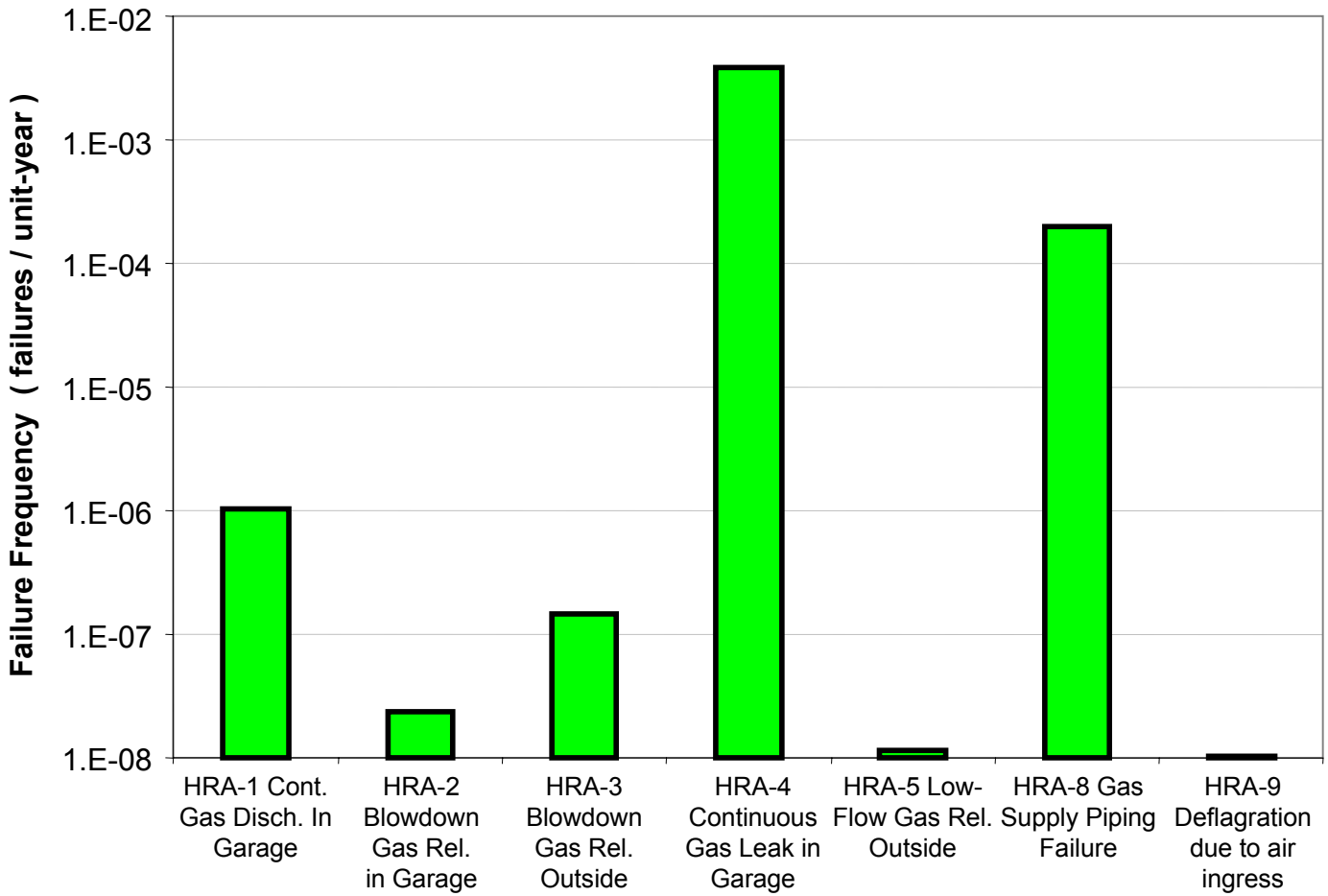
1 Approach

2 Supporting Analyses

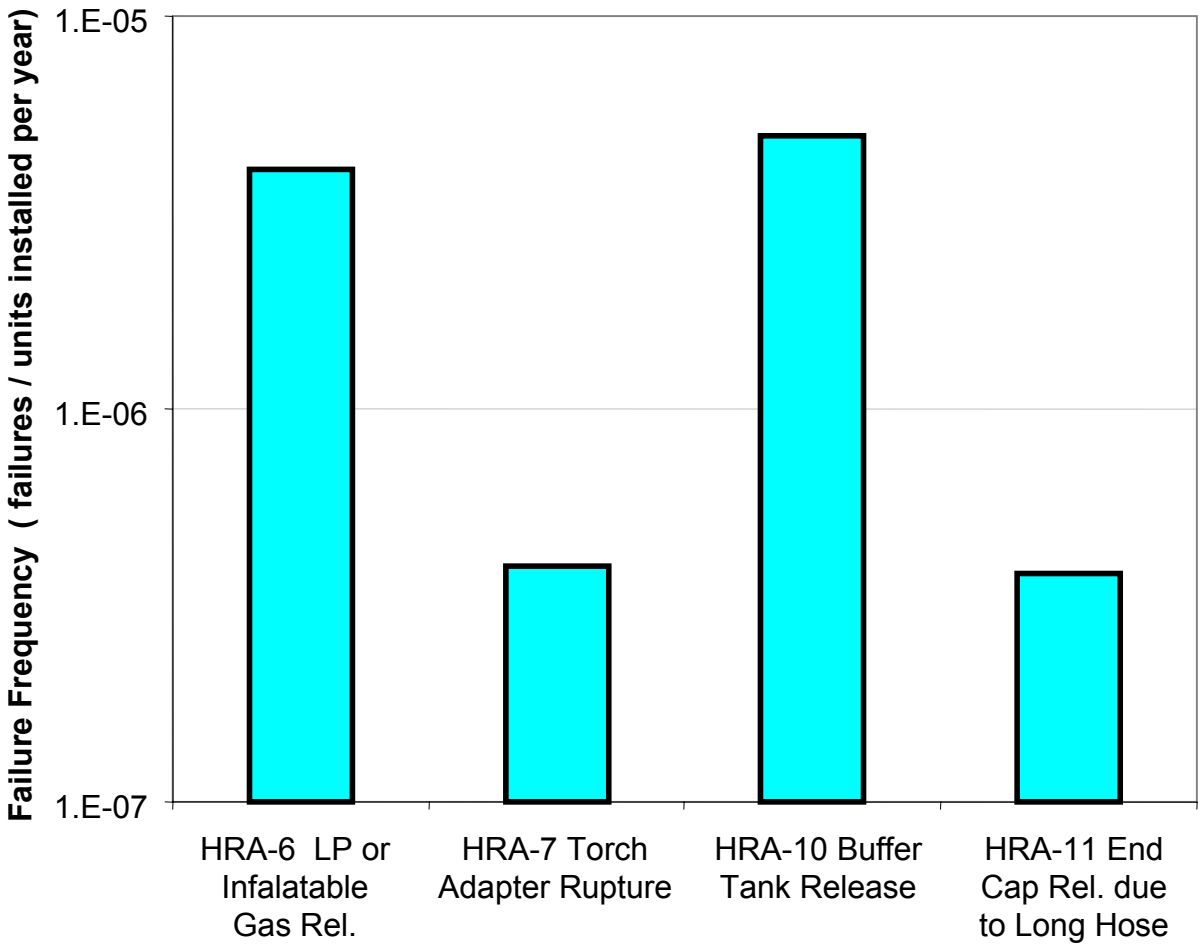
3 **Safety Evaluation Results**

4 Current Status

FTA results with top event frequencies expressed as failures/unit/year



FTA results with top event frequencies expressed as failures/units installed/year



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- Initial ETA focused on structure fires and deflagrations as most serious failure consequences
  - Frequencies predicted for each FTA top event
  - Cumulative frequencies calculated as sum
- Initial FTA/ETA based on HRA design/operation scenario no longer current
  - Assumed HRA cooling air discharge into garage
  - FuelMaker's recent additional leak check feature not included in the FTA's
- Initial FTA/ETA being revised
  - Incorporate outside venting of HRA cooling air
  - Incorporate additional leak check feature
  - Re-evaluate select failure/consequence frequencies
- Revision complete May 2004